Pete Klein
5733 Hwy 23
Ridgway, Co.
81432

1186338 - R8 SDMS

FIRST CLASS

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Wayne Webster
Box 132
Rico, Co. 81332

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TUNNEL BULKHEADS FOR ACID MINE DRAINAGE

Donald S. Einarson
Chief Design Engineer
American Mine Services, Inc.

and

John F. Abel, Jr.
Professor of Mining Engineering
Colorado School of Mines

Abstract

Concrete tunnel bulkheads designed to contain acid mine drainage water must be: (1) long enough to prevent leakage along the contact between the concrete and the rock, (2) thick enough to prevent shear failure in either the concrete or rock, (3) either thick enough to prevent tensile failure of the downstream face or contain sufficient tensile reinforcement to support the tensile stress, (4) deep enough to prevent hydrofracturing of the formation and (5) acid resistant enough to last the requisite time interval. The available design data includes in descending order of confidence, the strength of the concrete and steel, if used, the strength of the rock, the water head and the in situ stress field.

The cost of rehabilitating an old mine tunnel dictates that bulkheads be placed as close to the portal as possible. The only factor preventing the placement of a bulkhead in the first competent rock inside the portal is the necessity to prevent hydrofracturing of the formation. If the hydraulic pressure behind a bulkhead exceeds the compressive hoop stresses in the rock adjacent to the bulkhead, acid mine drainage water will probably be lost to the joint system.

The reinforced concrete bulkhead designed for the 10 by 10-ft Friday Lowden Tunnel in California calls for a 14-ft long bulkhead with #8 rebar on 9-in. centers each way. The owner stipulated a safety factor of 2 be applied to the design. As such, additional concrete thickness is required. The

bulkhead is to be low-pressure grouted to increase leakage resistance along the plug/rock contact. The length of the bulkhead is designed to prevent shear of the 3,000 psi concrete. The rebar is designed to resist any potential bending stresses that may develop. The mimimum depth of 127 ft below the surface is designed to prevent hydrofracturing.

The probable effectiveness of the 14-ft long low-pressure grouted bulkhead designed for the Friday Lowden is indicated by a 6-ft thick ungrouted lightly reinforced concrete bulkhead previously installed. This initial bulkhead was installed 255 ft in from the Friday Lowden Tunnel portal, at a depth of 62 ft below the surface, and tested under 212 ft of water head. The eventual plugging of three upper level portals in the Mammoth Mine will probably result in the greater water head of 670 ft. The new low-pressure grouted bulkhead is to be installed in competent rock 613 ft in from the Friday Lowden Tunnel portal, at a depth of approximately 150 ft below the surface. The new bulkhead is designed to support slightly more than three times the hydraulic head applied to the original bulkhead.

Introduction

The design of concrete bulkheads to resist hydraulic pressure in mines is well documented. First, it is necessary to have a long enough plug to prevent leakage along the contact between the concrete and rock, around the outside of the bulkhead. Second, it is necessary to have a long enough plug to prevent shear failure either in the concrete or the rock. Third, the tensile bending stress that may develop at the downstream face of the plug must either be kept below American Concrete Institute (ACI) allowable limits for plain concrete or steel tensile reinforcement must be added near the downstream face. For thinner bulkheads, steel reinforcement for shrinkage and temperature stress crack control is advisable for both ends of the bulkhead. Near surface bulkheads designed to prevent acid mine drainage have three additional requirements. The bulkhead must be as close to the portal as possible to minimize tunnel rehabilitation and bulkhead construction costs. The depth of near surface bulkheads must be sufficient to prevent formation breakdown at the design hydraulic pressure, i.e. hydrofracturing. Finally, data must be obtained for the rock and water quality to permit design. The piping through the bulkhead and concrete must not be destroyed by corrosion or chemical reaction with the acid mine water during the life of the plug.

The bulkhead design for the 10-ft wide by 10-ft high Friday Lowden Tunnel near Redding, CA is presented as an example bulkhead design. A plan and section of the Friday Lowden portal area is presented in Figure 1. The Friday Lowden Tunnel served as a haulage tunnel for the Mammoth Mine. A 6-ft thick lightly reinforced concrete bulkhead had already been designed and installed 255 ft in from the portal at an overburden depth of 62 ft. This concrete bulkhead was not grouted, either at low pressure along the concrete/rock contact or at high pressure in the rock adjacent to the tunnel. This bulkhead had been tested with an hydraulic head of 212 ft. There was no leakage around this bulkhead at the 92 psi hydraulic pressure.

This bulkhead was not effective because the acid mine drainage simply was diverted to the North Lower Gossan portal of the lowest mining level, approximately 212 ft above the Friday Lowden bulkhead. Therefore, it was necessary to remove the existing bulkhead, design a new bulkhead for the Friday Lowden and design bulkheads for the three higher mining level portals. The design maximum hydraulic head is the head that could develop when the Mammoth Mine is filled to the level of the lowest point around the surface subsidence, cave, area on the east face of Mammoth Butte. Obviously, it would not be possible to hydraulically seal the surface subsidence fractures and the cave above the major collapsed mining stopes in the Mammoth Mine. This results in a design hydraulic head of 670 ft for the Friday-Lowden Tunnel.

Bulkhead Design

A bulkhead for a tunnel must be in intimate contact with the tunnel walls to prevent leakage around the plug. Bulkhead failure by leakage around the bulkhead, in the case of mine bulkheads, is more likely than failure of the bulkhead under thrust. Loofbourow in the Society of Mining Engineers (SME) Mining Engineering Handbook (1973, sec 26.7.4) states "no indication of structural failure resulting from thrust was noted" in the case of ten bulkheads subjected by hydraulic pressures in excess of 1000 psi and which relied solely on normal rock surface irregularities. High hydraulic pressure gradients can be achieved by placing a long plug with a low resistance to water flow or by placing a short plug with high resistance to water flow. The shear strength of the concrete and the rock must be sufficient to prevent shear failure across the design length of plug and along the concrete and rock interface. The depth of the bulkhead must be sufficient to prevent hydrofracing of the formation. Finally, the plug must either be sufficiently long to accept the initial chemical attack of the acid mine drainage or it must resist the chemical attack of the acid mine drainage.

Bulkhead Pressure Gradient

The pressure gradient (Pg) across a bulkhead is the hydraulic pressure, in psi, divided by the thickness of the bulkhead, in ft. The pressure gradient for the original 6-ft thick bulkhead in the Friday Lowden Tunnel when subjected to the measured 212 ft of head was 15.3 psi/ft, calculated as follows:

$$Pg = 212(62.4)/144(6) = 15.3 \text{ psi/ft} \qquad (1)$$

This original bulkhead was neither grouted along the concrete/rock contact nor in the rock adjacent to the bulkhead. This measured value serves as a site specific indication of minimum hydraulic resistance along an ungrouted concrete/rock contact.

Garrett and Campbell Pitt (1961) reported the results from 26 mine bulkheads, more than half of which relied solely on the irregularity of the tunnel walls. The majority of the bulkheads were neither hitched, tapered nor reinforced. They reported extensive and obvious leakage along one ungrouted bulkhead in quartzite at a pressure gradient of 9.8 psi/ft. However, they presented a graph which indicates that an ungrouted plug should be able to withstand a pressure gradient of approximately 21 psi/ft at a factor of safety of one. They also recommend a minimum factor of safety of 4 in good rock, yielding a recommended maximum pressure gradient of just over 5 psi/ft.

Garrett and Campbell Pitt indicated that low-pressure grouting of the concrete/rock contact would permit pressure gradients of 165 psi/ft without obvious leakage. Applying a factor of safety of four produces a design pressure gradient of over 41 psi/ft. The indicated benefit from grouting the concrete/rock interface is an eightfold decrease in bulkhead length.

Garrett and Campbell Pitt indicated that high-pressure grouting of the rock adjacent to a bulkhead will result in a considerable increase in the allowable pressure gradient across the plug. However, high-pressure grouting is not an option for near surface plugging of old mine tunnels. Near surface high-pressure grouting will result in hydrofracing of the rock around the tunnel.

The Society of Mining Engineers (SME) Mining Engineering Handbook (1973) recommends, in section 26.7.4, 40 to 25 ft of plug length for each 1000 psi of hydraulic head, i.e. pressure gradients from 25 to 40 psi/ft. The recommended concrete/rock grout pressure is "a few hundred psi". In practice, the grouting pressure must be kept below the formation breakdown pressure to prevent hydrofracing. This limitation is particularly important for near surface bulkheads in order to prevent acid water communication to the ground surface.

The mean uniaxial compressive strength of the igneous rock adjacent to the Friday Lowden bulkheads was measured at 15,570 psi. This relatively massively jointed rock would be considered good rock. The only permeability in this rock is along fractures. It would appear reasonable that the initial ungrouted bulkhead in the Friday Lowden Tunnel was functioning near capacity at the 15.3 psi/ft pressure gradient and could not be relied upon to withstand the planned ultimate pressure gradient of 48.4 psi/ft, under the maximum planned head of 670 ft, without excessive leakage.

The length required for an ungrouted bulkhead for the Friday Lowden Tunnel is 19 ft for the 15.3 psi/ft in the case of reproducing the original ungrouted bulkhead to support the 670-ft head. A bulkhead length of 58 ft is required in the case of 5 psi/ft for an ungrouted plug and 7 ft for a low-pressure grouted concrete/rock contact following the Garrett and Campbell Pit recommendations. A bulkhead length between 7 and 12 ft is required following the SME recommendations. The owner required that the bulkhead meet the requirement of an additional factor of safety of 2. It was therefore decided to design a 14-ft long bulkhead to resist the hydraulic pressure anticipated for the Friday Lowden.

Shear Strength Design

The length of a bulkhead must be sufficient to keep the shear stress developed in the bulkhead concrete below the ACI limits (ACI, 1983, sec 11.3) and the shear stress in the adjacent rock to well below its estimated shear strength. The ACI estimated minimum shear strength of the design 3,000 psi compressive strength concrete for the Friday Lowden bulkhead is:

$$v_c = 2\sqrt{3000} = 110 \text{ psi} \tag{2}$$

The owner required additional factor of safety of 2 reduced the design shear strength to 55 psi. Applying the same design method to the 15,570 psi uniaxial compressive strength of the rock adjacent to the planned Friday Lowden bulkhead results in a design shear strength of 125 psi, including the additional factor of safety of 2. This calculated shear strength for the rock seems to be extremely low, which is probably actually on the order of approximately 2,000 psi. Irregardless, the concrete shear strength will govern the shear design for the Friday Lowden Tunnel bulkhead.

The simple shear strength design, assuming shear would take place just inside the concrete/rock interface, is as follows:

$$\text{Required plug length (ft)} = pab/2(a+b)v_c \tag{3}$$

p = pressure head (psi)
a = width (ft)
b = height (ft)
v_c = shear strength (psi)

$$\text{Required plug length (ft)} = 290(10)(10)/2(10+10)55 = 13.2 \text{ ft}$$

Therefore, the 14-ft design plug length for the pressure gradient criteria is acceptable for ribside shear.

The ACI (1983, sec 11.8) provides guidance for ultimate strength shear design for deep beams, where the span divided by the beam depth ratio is less than 5. The Friday Lowden span/depth ratio for the 10-ft span by planned 14-ft length plug, deep beam, is 0.71. Using the ACI deep beam design procedure involves the conservative assumption that the bulkhead carries load from side to side acting as a one-way slab, but no load from roof to floor of the tunnel. The design procedure further uses a one-foot wide strip of the slab. The critical section for design is defined as 0.15 times the span in from the ribside for uniformly loaded beams, 1.5 ft in the case of the 10-ft wide Friday Lowden Tunnel. The ACI specified shear strength (v_c) that is available at the critical section for unreinforced deep beams with a span to depth ratio of less than five is:

$$v_c = K(1.9\sqrt{f'c}) \tag{4}$$

f'c = design concrete strength (psi)

$$v_n = \phi\, v_c \tag{5}$$

ϕ = 0.85 capacity reduction factor for concrete in shear
v_n = nominal available shear strength (psi)

$$K = 3.5 - 2.5M_u/V_u(d) \tag{6}$$

M_u = critical section moment (ft-lb)
V_u = critical section shear (lb)
d = beam depth (ft), plug length

Except K cannot exceed 2.5 and v_c cannot exceed $6\sqrt{f'c}$

For the Friday Lowden bulkhead Mu is 372,708 ft-lb, as follows:

$$M_u = (w\ell/2)(0.15\ell) - w(0.15\ell)(0.15\ell)/2$$

w = hydrostatic load (lb/ft)
ℓ = tunnel width (ft)

$$M_u = 0.075w\ell^2 - 0.01125w\ell^2 = 0.06375w\ell^2$$

ACI specifies that the design strength (U) provided to resist the actual hydrostatic load (F), in this case the hydraulic pressure exerted on the upstream face of the bulkhead, equal 1.4 times the actual hydrostatic load.

$$U = 1.4(p)(144) \text{ lb/ft} \qquad (7)$$
$$U = 1.4(290)(144) = 58{,}464 \text{ lb/ft}$$

p = hydraulic pressure (psi) to be substituted for the actual uniform loading (w) on the upstream face of the bulkhead.

$$M_u = 0.06375(58464)(10^2) = 372{,}708 \text{ ft-lb}$$

$$V_u = (w\ell/2) - (w\ell/2)(0.15\ell/0.5\ell) = 0.5w\ell - 0.15w\ell$$
$$V_u = 0.35\ w\ell = 0.35(58464)10 = 204{,}624 \text{ lb}$$

Therefore, the calculated K, equation (6), for the planned 14-ft long bulkhead in the Friday Lowden Tunnel is:

$$K = 3.5 - 2.5(372708/(204624)(14) = 3.5 - 0.325 = 3.175$$

Since the calculated K is greater than 2.5, the ACI requires that 2.5 be used in calculating the nominal permissible shear stress at the critical section, as follows:

$$v_c = K(1.9\sqrt{f'c}) = 2.5(1.9\sqrt{3000}) = 260 \text{ psi}$$

$$v_n = 0.85(260) = 221 \text{ psi}$$

This permissible value had to be divided by two to meet the owner's additional requirement, yielding a maximum allowable design stress of 111 psi. The ACI limiting value for the permissible shear stress, v_c, is $6\sqrt{f'c}$, or 329 psi.

The calculated actual shear stress (v_u) for the critical section is the shear force (V_u) present at the critical section divided by the area of the section, as follows:

$$v_u = V_u/d = 204624/(14)(144)(1) = 102 \text{ psi} \tag{8}$$

The ACI further states that the actual shear stress (v_u) at the critical section shall not exceed $8\ \phi \sqrt{f'c}$, or 372 psi, for deep beams with span/depth ratios less than 2. When this limiting value is divided by, the owner required, 2 the limiting value is 186 psi. The actual calculated shear stress (v_u) of 102 psi at the critical section is less than both the 111 psi maximum allowable shear stress (v_c) and the 186 psi critical section limiting shear stress. Therefore, the 14-ft long plug designed for the Friday Lowden pressure gradient requirement is adequate to meet the shear strength requirement.

Bending Strength Design

It is difficult to obtain good adhesion between the concrete bulkhead and the roof and floor of a tunnel. The difficulty lies in completely cleaning of the floor and keeping it clear of mud and rock until the concrete is poured and in completely filling all the voids in the roof. As a result the analysis of bending was based on a simply supported beam anchored at the walls of the tunnel. This conservative design approach can be further justified by the inability of obtaining access to the upstream side of a bulkhead and the long life expected of the plugs.

The first bending analysis performed is to calculate what length of unreinforced, plain, concrete bulkhead is necessary to keep the tensile bending stresses in the down stream face below ACI allowable stress. ACI (1977, sec 9.3.2) directs that a capacity reduction factor of 0.65 be used in design. Further ACI (sec 15.11.1) directs that the design tensile bending strength be:

$$f_t = 5\sqrt{f'c} \tag{9}$$

This amounts to 273 psi for the 3,000 psi concrete to be used in the Friday Lowden Tunnel bulkhead. The owner required factor of safety reduces this design strength to 137 psi. ACI also requires a 1.4 load factor for dead weight loads, such as hydraulic pressure. The required length of an unreinforced plain concrete bulkhead is calculated as follows:

Pressure (dead) load per ft (w) - (1.4)290(144) - 58464 lb/ft

Maximum bending moment (M_u) - $w\ell^2/8$ (10)

M_u - 58464(10^2)/8 - 730,800 ft-lb

Nominal design bending moment adjusted for capacity reduction factor of 0.65 is:

M_n - 730800/0.65 - 1,124,308 ft-lb

Maximum flexural stress (psi) - M_n/S (11)

S - section modulus (in.^{3})

Section modulus (in.^{3}) - I/c (12)

I - moment of inertia (in.^{4})

c - centroidal distance (in.)

Moment of inertia (in.^{4}) - $bh^3/12$ (13)

b - beam width (in.)

h - beam depth (in.)

Centroidal distance (in.) - h/2 (14)

Therefore, flexural stress (psi) - M_n/S - $M_n/[(bh^3/12)/(h/2)]$

f_t - $(6)M_n/bh^2$ (15)

Required length (h) of plain concrete bulkhead, obtained by solving equation (15) for the beam depth (h), bulkhead length:

$$h^2 = (6)M_n/b(f_t) = (6)1{,}124{,}308/137(144)(1) = 342$$
$$h = 18.5 \text{ ft}$$

The alternative to a plain concrete bulkhead is to install tensile reinforcement to carry the tensile bending stresses. The ACI capacity reduction factor for bending in reinforced concrete (ACI, 1983, sec 9.3.2.1) is 0.90. The method employs the rectangular compressive stress distribution approximation. The ACI method is described in sec 10.2 and assumes that a uniform compressive stress equal to 0.85 times the specified concrete compressive strength acts over an area 1 ft wide by 0.85 times the centroidal distance in depth (a) below the loaded surface. The constant, 0.85, is reduced 0.05 for each 1,000 psi the concrete strength exceeds 4,000 psi. The method, as further described by Wang and Salmon (1985, p 43-44), assumes the tensile reinforcing steel yields before the concrete crushes under bending induced compressive stress.

The tensile reinforcement design for the 14-ft thick Friday Lowden, Bulkhead follows:

$$\text{Compressive force (C)} = 0.85(f'c)ba \tag{16}$$

$$\text{Tensile force (T)} = A_s f_y \tag{17}$$

b = beam width (in.)
a = compression zone depth (in.)
A_s = steel area (sq in./ft)
f_y = steel yield stress (psi)
$f'c$ = concrete strength (psi)

The method presented by Wang and Salmon (1985) assumes that the compressive stress concrete area is no deeper into the beam than necessary to carry the bending moment developed compressive force at the ACI specified compressive stress of 0.85 times the specified compressive strength. The calculations for the Friday Lowden bulkhead follow.

Equating C to T using equations (16) and (17):

$C = T \qquad 0.85(f'c)ba = A_sf_y \qquad 0.85(3000)12a = 60000A_s$

$a = A_sf_y/0.85(f'c)b = 60000A_s/0.85(3000)12 = 1.96078A_s$

Summation of moments about center of compressive stress area using equation (18), note: rebar embedment is 3 in. (0.25 ft)

$$M_n = A_sf_y(d - a/2) \tag{18}$$

d = depth from top of beam to center of reinforcing steel (in.)
M_n = Nominal moment capacity (in.-lb)

$$M_n = A_sf_y(d - a/2) = 60000A_s[(14 - 0.25)12 - 1.9\overset{6}{\wedge}078A_s/2]$$
$$M_n = 60000A_s(165 - 0.98039A_s) = 9900000A_s - 58824A_s^2 \text{ ft-lb}$$

The design moment is also:

$$M_n = (M_u/\phi)(12) \text{ in.-lb} \tag{19}$$

Solution for reinforcing steel area:

$$730800(12)/0.90 = 9900000A_s - 58824A_s^2$$
$$58824A_s^2 - 9900000A_s + 9744000 = 0$$

Therefore, the required As = 0.990 sq in./ft of beam.

Rebar specification, to resist the maximum bending moment, is #8 bars on 9-in. spacing which provides 1.05 sq in. of steel per foot of beam which will supply a 861,000 ft-lb bending moment resistance. The design bulkhead thickness typically required to prevent leakage due to the pressure gradient and to resist shear forces makes the use of a simple beam design for bending extremely conservative. The bending deformations causing appreciable reinforcing steel strain, and therefore tensile stress, will not be linear due to the bulkhead thickness and the lateral restraint provided by the tunnel ribs. Bulkhead failure would most likely occur by concrete yielding of a pressure arch that would develop in the upstream side, rather than as the result of yielding of the reinforcing steel. Therefore, a safety factor of 2 through an increase in the quantity of reinforcing steel was not made in this case. Some reinforcing steel is advisable in the downstream side to control temperature and shrinkage induced stresses. The quantities of steel indicated by the simple bending analysis do not appear to be excessive for typical tunnel sizes.

Bulkhead Depth Based on Hydraulic Pressure

Hydrofracturing, generally referred to as hydrofracing, of sedimentary formations from drillholes is frequently undertaken for the purpose of stimulating oil well production. Formation breakdown pressure (Bp) is a function of (1) the tensile strength of the rock immediately adjacent to the drillhole, (2) the in situ stress field in the plane perpendicular to the drillhole and (3) the pore pressure present in the formation. Bredehoeft, et al (1973) presented a study of hydrofracing a competent rock from drillholes. They presented the following well-known equation for breakdown pressure:

$$Bp = Ts + 3Smin - Smax - Pf \qquad (20)$$

All terms in psi

Ts - tensile strength
Smin - minimum stress normal to the borehole
Smax - maximum stress normal to the borehole
Pf - formation pore pressure

The equation can be simplified for the case of hydraulic pressure behind an acid mine drainage bulkhead in a tunnel. First, the tensile strength can be assumed to be zero because the rock adjacent to a tunnel is jointed and generally damaged by blasting. The packed section of a drillhole, on the other hand, can be entirely within one joint block and is not subject to blasting. Second, the pore pressure present near surface and adjacent to a tunnel must be low and can be assumed to be zero. Finally, in the absence of in situ stress measurements it is necessary to estimate the stresses in the plane normal to the tunnel. The simplest assumption is for hydrostatic stress conditions equal to the overburden stress. The assumption is generally conservative since the overburden stress must be present and the more general stress state measured is for the horizontal stresses to equal or exceed the overburden stress. Normal formation breakdown pressures encountered in oil field work range from 1.4 to 2.8 times the overburden stress. This indicates that the hydrostatic stress assumption, where the breakdown pressure equals two times the overburden stress, is not unreasonable.

The resulting simplified breakdown pressure equation is:

$$Bp = 2Sovb \tag{21}$$

Sovb = overburden stress (psi)

Therefore, any acid mine drainage bulkhead must be placed at a depth which will not result in hydrofracing the rock adjacent to the tunnel, i.e. opening of the joints and fractures and injection of acid mine water into the rock mass, around the plug or to the ground surface.

The hydraulic breakdown pressure (Bp) available to hydrofrac the rock up stream from the plug and adjacent to the tunnel is the maximum potential head. Therefore, the overburden stress must be sufficient to prevent hydrofacing. The required overburden stress (Sovb) is:

$$Sovb = Bp/2 \tag{22}$$

The overburden pressure is the product of the depth (H) and density (γ) of the overlying rock. Since the density can be readily measured, the depth of the bulkhead must be selected to limit the possibility of hydrofracing, as follows:

$$Sovb = \gamma(H)/144 = Bp/2 \tag{23}$$

γ = density (PCF)
H = depth (ft)

$$H = 72Bp/\gamma \tag{24}$$

In the case of the Friday Lowden bulkhead the required depth is greater than 127 ft for the 165 PCF overburden rock density and the 290 psi maximum hydraulic pressure, as follows:

$$H - 72(290)/165 - 127 \text{ ft}$$

Corrosion Resistant Design

The critical portion of any bulkhead with respect to corrosion is the piping that penetrates through the concrete. Pipe penetrations are necessary to pass mine drainage through the bulkhead during construction. In addition, some means is necessary to permit release of impounded water if required at some time in the future. It is also wise to be able to monitor water pressure behind the bulkhead in order to determine the elevation of any unanticipated leakage.

The corrosion rates and the resulting probable life of piping of various stainless steels and pipe diameters were evaluated. This analysis used the approximate acid mine water concentrations and temperatures. Specific types of corrosion considered were aerated sulfuric acid; cupric, cuprous and ferric sulfate; cadmium sulfate; ferrous sulfate; and zinc sulfate. The maximum corrosion rate estimated for Carpenter 20Cb-3 stainless steel pipe by the manufacturer was less than 0.005 in./yr for the maximum solution concentration, the maximum pressure and the highest temperature. In addition, it was assumed that the solution concentrations were held constant. Two diameter pipes were analyzed, 6-in. and 1-in.

The design problem is to estimate when the strength of the corroded stainless steel piping will drop below the maximum hydraulic pressure (P). The Carpenter 20Cb-3 stainless steel has a yield strength of 55 ksi, which is reduced to 33 ksi for design. The minimum wall thicknesses required for the 290 psi hydraulic pressure at the Friday Lowden site are 0.053 in. for the nominal 6-in. diameter pipe and 0.009 in. for the nominal 1-in. diameter pipe. These values were calculated as follows:

$$P = 2St/D \tag{25}$$
$$P = 2(33000)t/D$$
$$P = 66000t/D$$

P = hydraulic pressure (psi)
S = fiber stress (psi)
2 – for two pipe walls
t = wall thickness (in.)
D = nominal diameter (in.)

This reduces to the minimum required wall thickness for the nominal 6-in. diameter Schedule 40 pipe for the Friday Lowden, as follows:

$$t = PD/66000 \tag{26}$$
$$t = 2(290)6/66000 = 0.053 \text{ in.}$$

Note: additional owner required factor of safety of 2.

The wall thickness of the Schedule 40 nominal 6-in. diameter pipe is 0.280 in. It will take approximately 45 years to reduce the original wall thickness to 0.053 in., as follows:

$$(0.280 - 0.053)/0.005 = 45 \text{ years}$$

The wall thickness for the Schedule 80 nominal 1-in. diameter pipe is 0.179 in. The calculations are, as follows:

$$t = 2(290)1/66000 = 0.009 \text{ in.}$$
$$(0.179 - 0.009)/0.005 = 34 \text{ years}$$

The corrosion rate for the concrete in the bulkhead will be reduced by using Type V sulfate resisting cement. In addition, the initial rate of acid attack will decrease rapidly because once the bulkhead valves are closed no fresh solution will contact the concrete.

Summary

Near surface concrete tunnel bulkheads can be safely designed to impound acid mine water by considering the leakage potential along the concrete/rock contact, the shear stress developed in the concrete and the rock, the bending moment resistance of the bulkhead, the hydrofracturing potential and the corrosion rates for the piping and concrete. Low-pressure grouting of the concrete/rock contact is recommended to increase the hydraulic gradient resistance between the plug and the rock and to decrease the length of the bulkhead. The shear strength of the concrete and the rock must exceed the shear stress for the maximum head. The bending stress at the downstream face must either be kept below allowable plain concrete design tensile strength or steel tensile reinforcement must be placed near the down stream face to support the potential tensile stresses. The bulkhead must be installed at a depth sufficient to prevent hydrofracing the formation and the loss of acid water to the joint system. The corrosion rate of the piping through the bulkhead must be balanced by sufficiently thick pipe walls to provide for the required minimum bulkhead life.

The final design of the Friday Lowden bulkhead as determined by the above analyses and presented as an example is shown on Figure 2.

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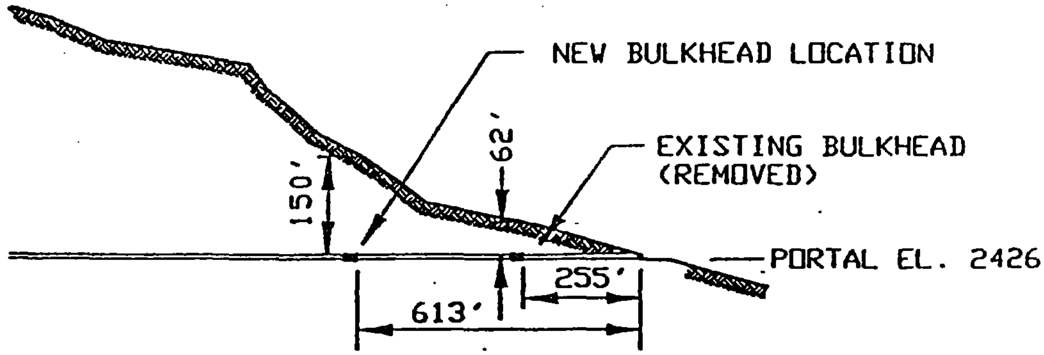
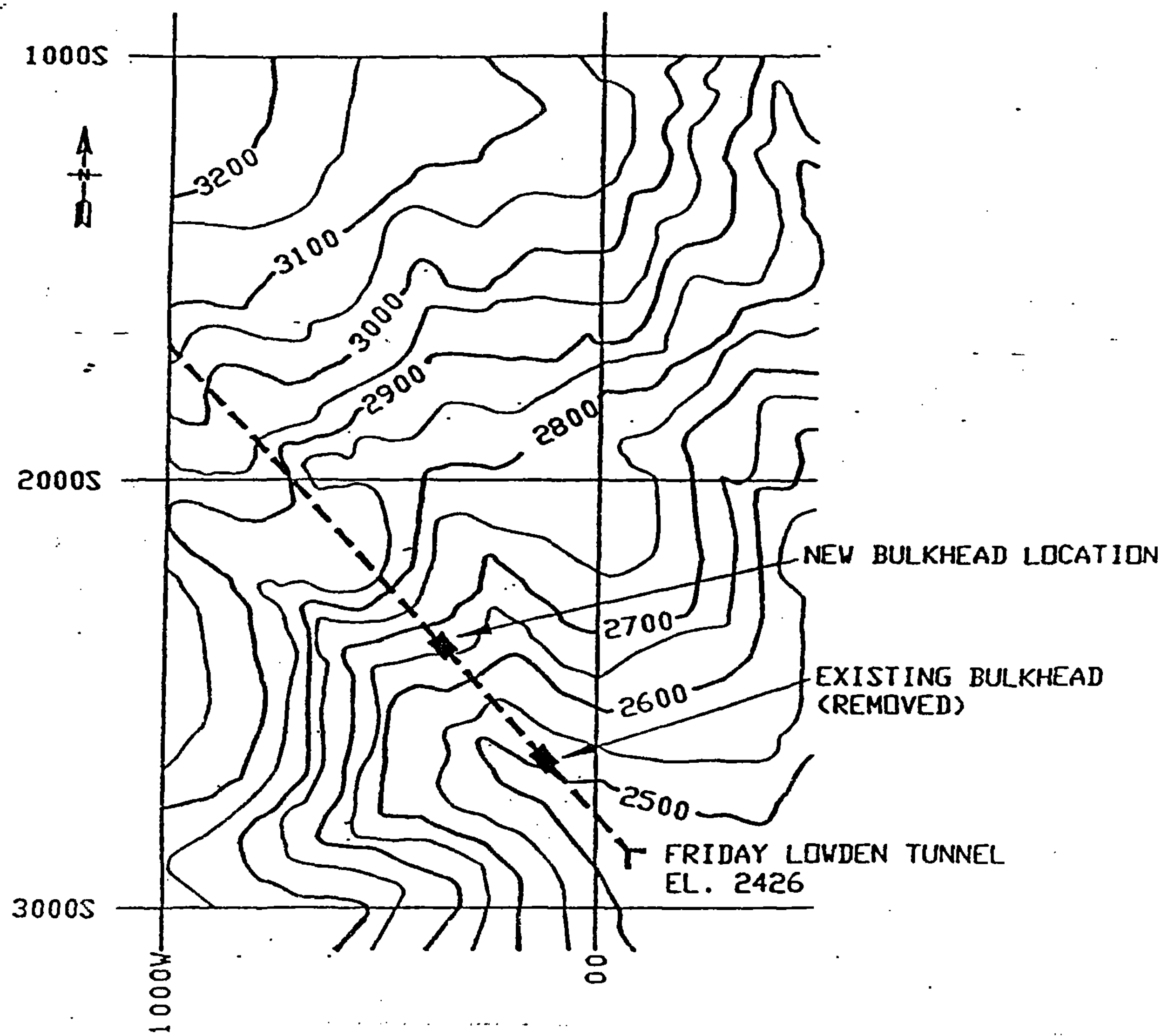
FRIDAY LOWDEN TUNNEL



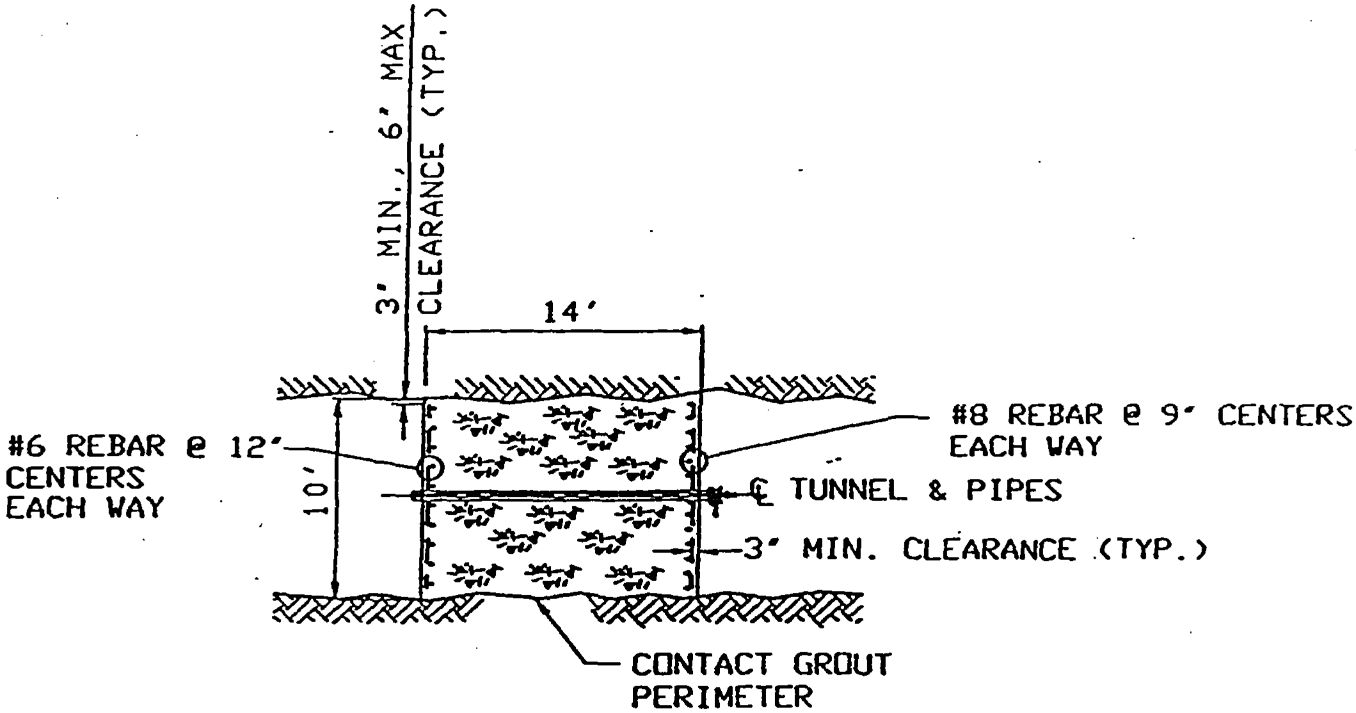
CROSS SECTION LOOKING NORTHEAST



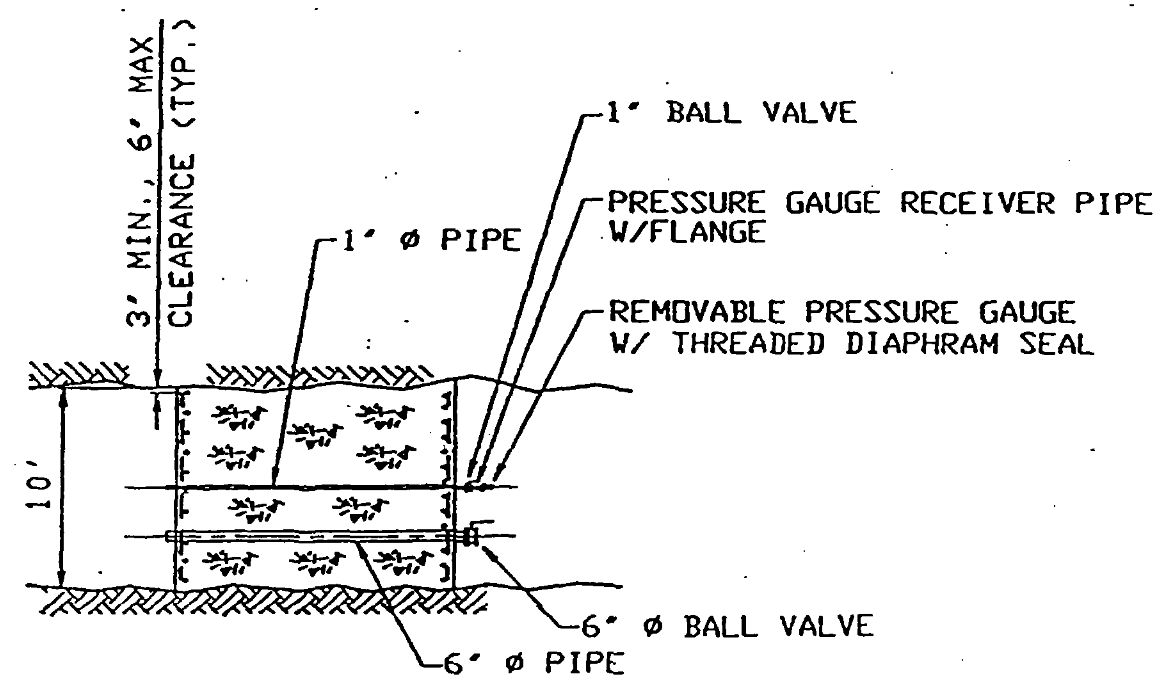
PLAN

FIGURE (1)

WATER CONTROL BULKHEAD
FRIDAY LOWDEN TUNNEL



PLAN



SIDE ELEVATION

FIGURE (2)